Cosmic-Ray Source Composition Determined from ACE

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EXTENDED ABSTRACT

The Advanced Composition Explorer (ACE) spacecraft was launched on 25 August 1997 into a halo orbit about the L1 Lagrange point, 1.5×10^6 km sunward of the Earth. Among the instruments it carries is the Cosmic Ray Isotope Spectrometer (CRIS) which covers the energy range from $\sim$ 50 to $\sim$ 500 MeV/nucleon and samples predominantly galactic cosmic-ray material. CRIS identifies the charge and mass of detected nuclei using the dE/dx versus total energy technique. Energy loss measurements are made in 4 stacks of large-area silicon solid-state detectors, and particle trajectories are derived from measurements made in a scintillating optical fiber hodoscope in front of the silicon stacks. An important feature of this instrument is its large geometrical acceptance, $\sim 250\text{cm}^2\text{sr}$, which is a factor $\sim$ 20 larger than has been available with previous space instruments of this kind.

The cosmic rays arriving at Earth comprise a mix of material produced by stellar sources and ejected into the interstellar medium ("primary" cosmic rays) and particles produced by fragmentation of heavier nuclei during transport through the Galaxy ("secondary" cosmic rays). The primary cosmic rays are of interest for the information they carry about processes such as stellar nucleosynthesis and particle acceleration by astrophysical shocks. The secondaries serve as probes of the transport of these high energy particle as they traverse the interstellar medium and interact with the gas and magnetic fields with that reside there. They also provide a measure of the corrections which must be made to the arriving abundances of mixed primary-plus-secondary species to obtain the source composition.

This paper addresses the source abundances derived from the measured cosmic-ray composition and their implications for the origin of cosmic rays. In another paper in this workshop (R. A. Mewaldt et al.), ACE results on secondary cosmic-ray abundances and their implications for cosmic-ray transport are discussed.

The best probes of the nucleosynthetic origins of cosmic rays are provided by those elements and isotopes that have little contamination from secondary fragments produced during galactic propagation. Among the "iron peak" elements Fe, Co, and Ni, there are 10 stable isotopes for which precise source abundances can easily be derived. In addition, among the intermediate-mass elements Ne, Mg, and Si there are an additional 8 dominantly-primary isotopes. For a number of other elements such as C, O, and S, there is one major isotope which has little contamination by secondaries, plus one or more minor isotopes for which source abundance derivations require precise determinations of secondary contributions. Another group of cosmic-ray isotopes, accessible for the first time with ACE, are those in the "ultraheavy" region (atomic numbers greater than 28). While these species are extremely rare, the large geometrical factor of the CRIS instrument has allowed the accumulation of sufficient statistics to examine the isotopic composition of Cu and Zn.

The most striking result from a comparison the abundances of these isotopes with corresponding abundances found in solar system material is that there is only one isotope, ^{22}Ne, for which the the compositions of these two samples of matter differ by more than a few tens of percent. This similarity is surprising for a variety of reasons. The solar system composition represents the abundances that were present in the interstellar medium approximately 4.5 billion years ago when the solar system formed and when the Galaxy was only about half of its present age. The cosmic rays, however, were only recently ($\sim$ 20 Myr ago) accelerated to high energies. The source material from which they were derived may be the gas and dust in the present day interstellar medium, which reflects a mix of contributions from stellar winds and supernovae over the age of the Galaxy. It should contain some recent contributions which one would expect would show the effects of chemical evolution of the Galaxy.

The mix of isotopes found in the solar system or in cosmic-ray source material can not be accounted for by nucleosynthesis in one type of star. Rather, they require contributions from the ejecta of supernovae of both type II (resulting from core collapse of massive, relatively young stars) and type Ia (resulting from accretion of a critical mass onto old, white dwarfs that evolved from low-mass stars). These objects have different spatial and temporal distributions, yet the mixes of their products found in solar system material and in the cosmic-ray source are very similar.

The non-solar isotopic composition of cosmic-ray neon, with its excess of ^{22}Ne, is of particular interest because of its uniqueness among the elements for which the cosmic-ray source isotopic abundances have been determined. Among the various suggestions for the origin of this anomaly, most recent attention has been given to the possible origin of ^{22}Ne in Wolf-Rayet stars. The winds of these very massive stars are sufficient to blow off the entire hydrogen-rich outer atmosphere leaving a surface rich in helium and helium-burning products. The isotope ^{22}Ne, which is formed as CNO nuclei are consumed during helium burning, would be greatly enriched in the surfaces of these stars. When ejected at relatively high velocities by the stellar winds, the ^{22}Ne-enriched material may be accelerated with particularly high efficiency by supernova-driven shocks.

In this paper we present ACE measurements of the abundances of range of cosmic-ray elements and isotopes. We compare these with results from previous cosmic-ray experiments, where available. In addition, we use a model of cosmic-ray propagation in the Galaxy, constrained by measured abundances of secondary nuclides, to derive the corresponding composition of cosmic-ray source material. We compare the inferred cosmic-ray source composition with abundances found in the solar system and in other samples of matter. We also compare with model predictions of the ejected yields from supernovae explosions. On the basis of these comparisons we discuss implications for the origin of cosmic rays.

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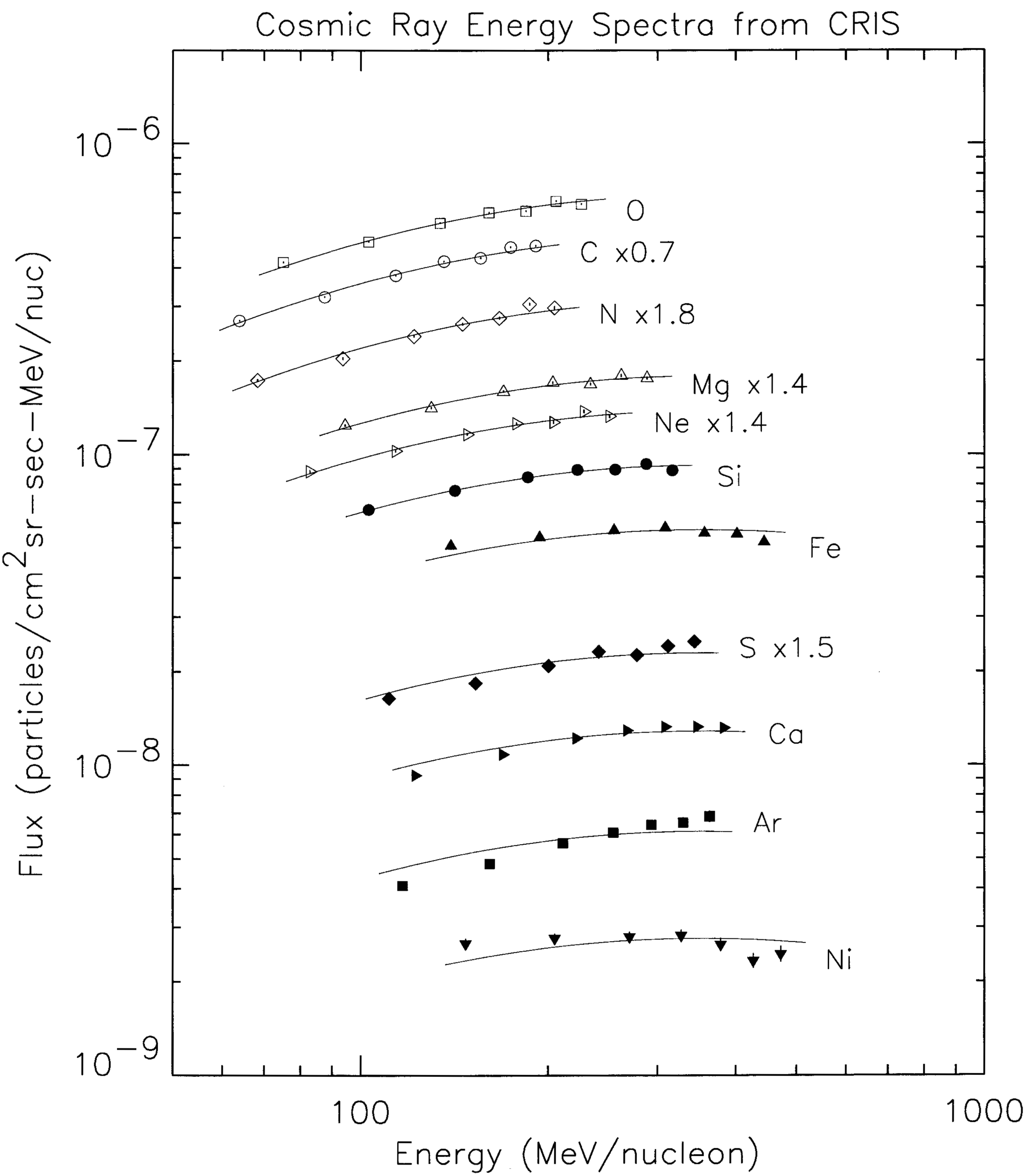

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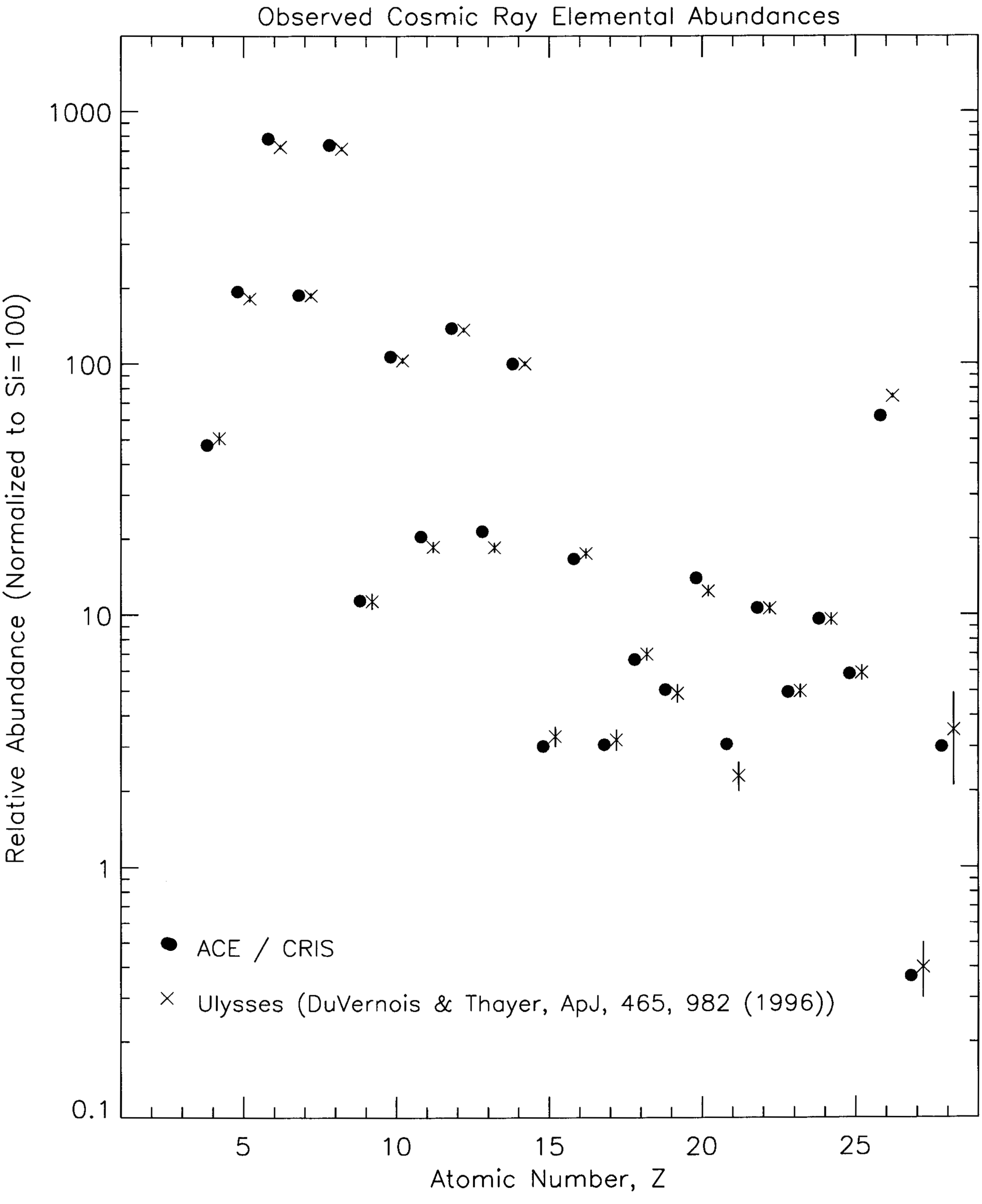

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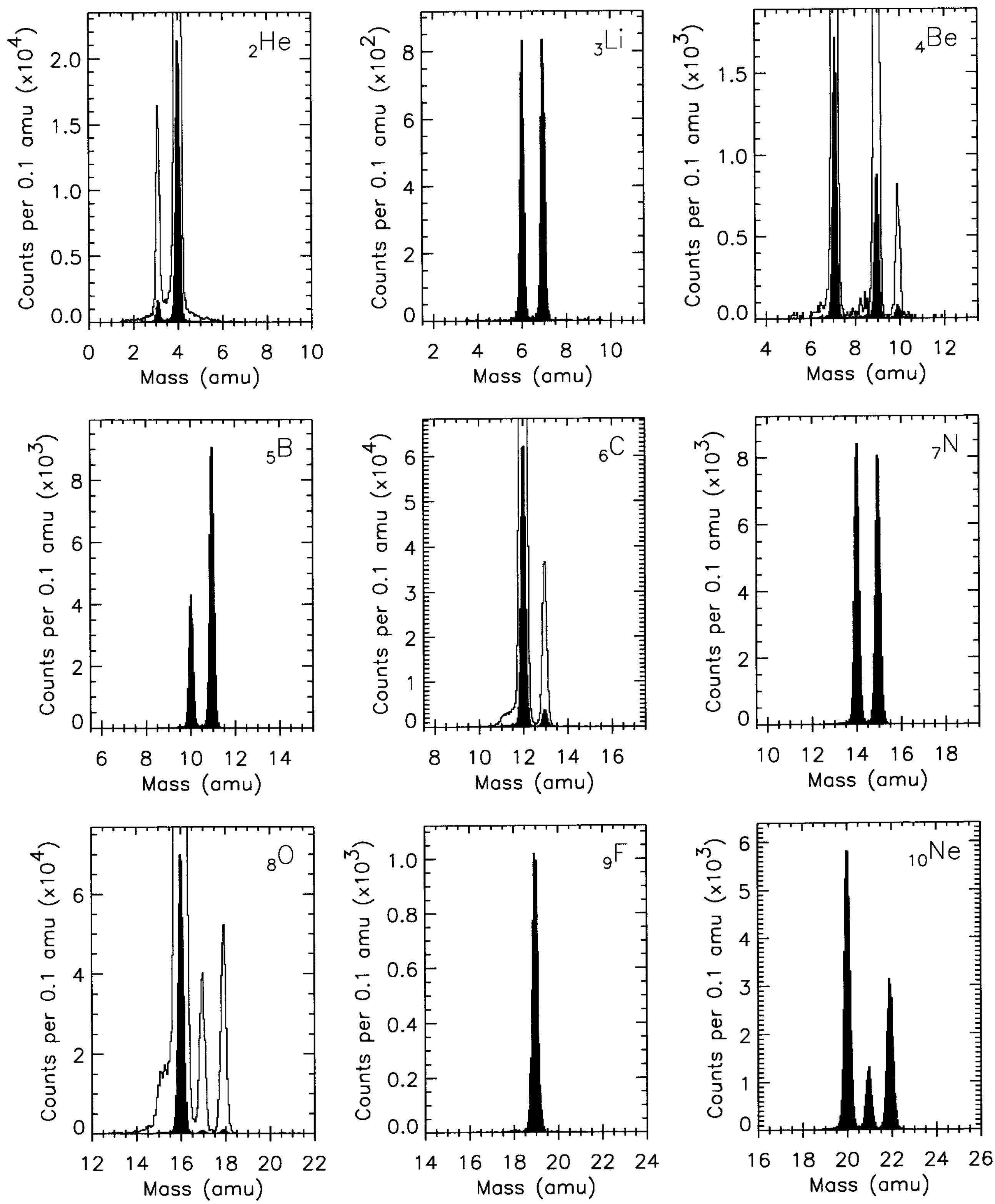
ACE/CRIS Measured Mass Distributions



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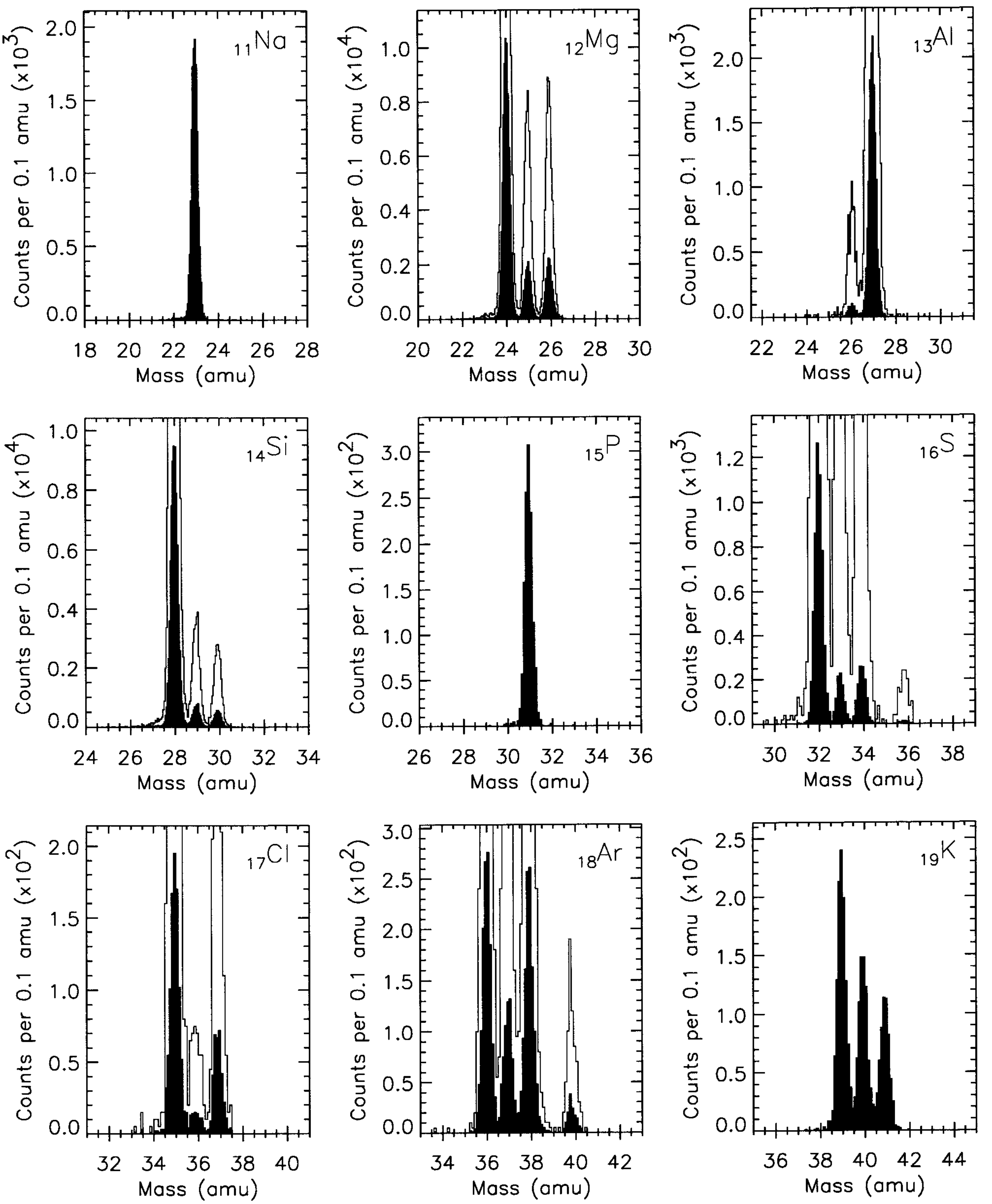

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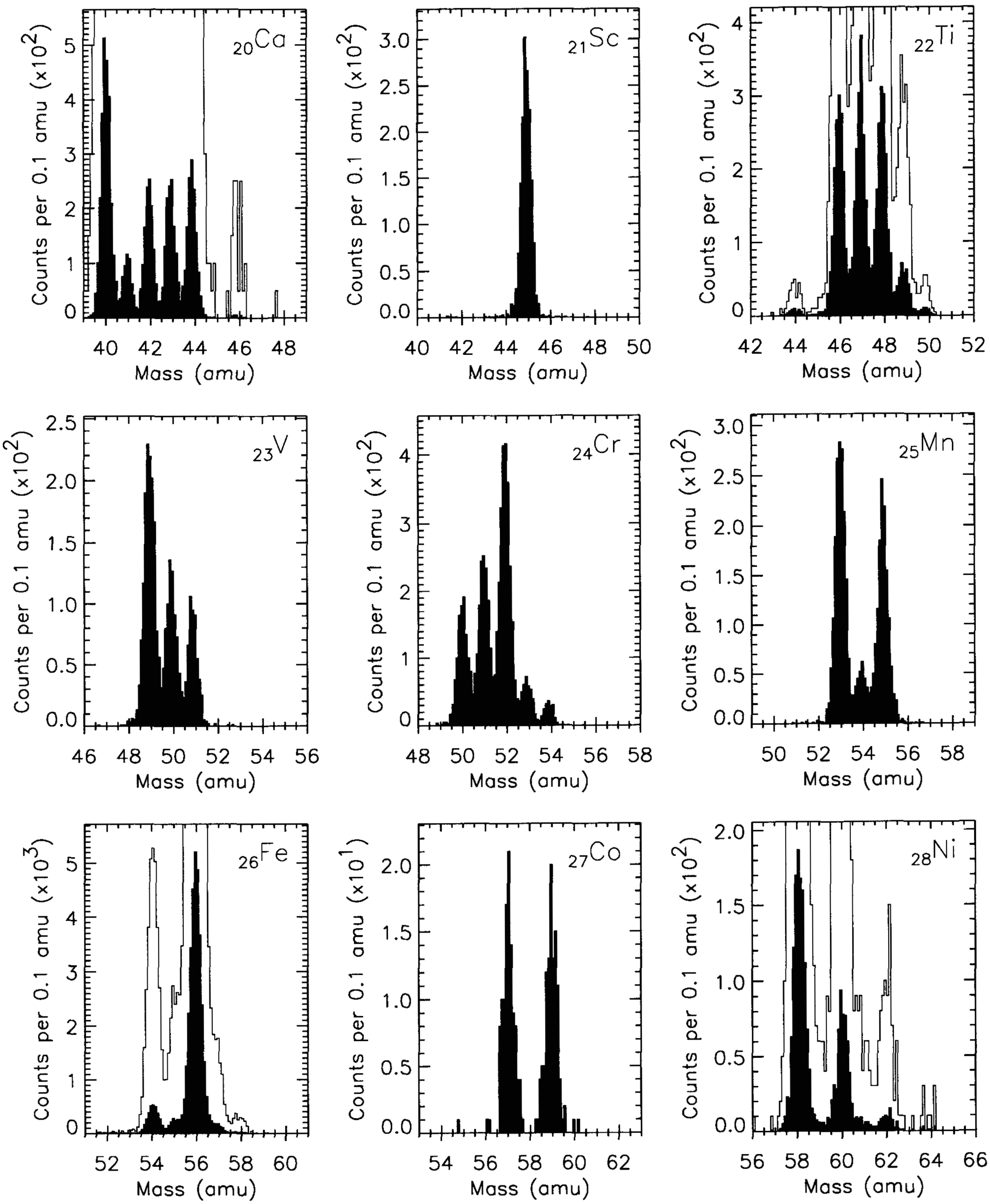

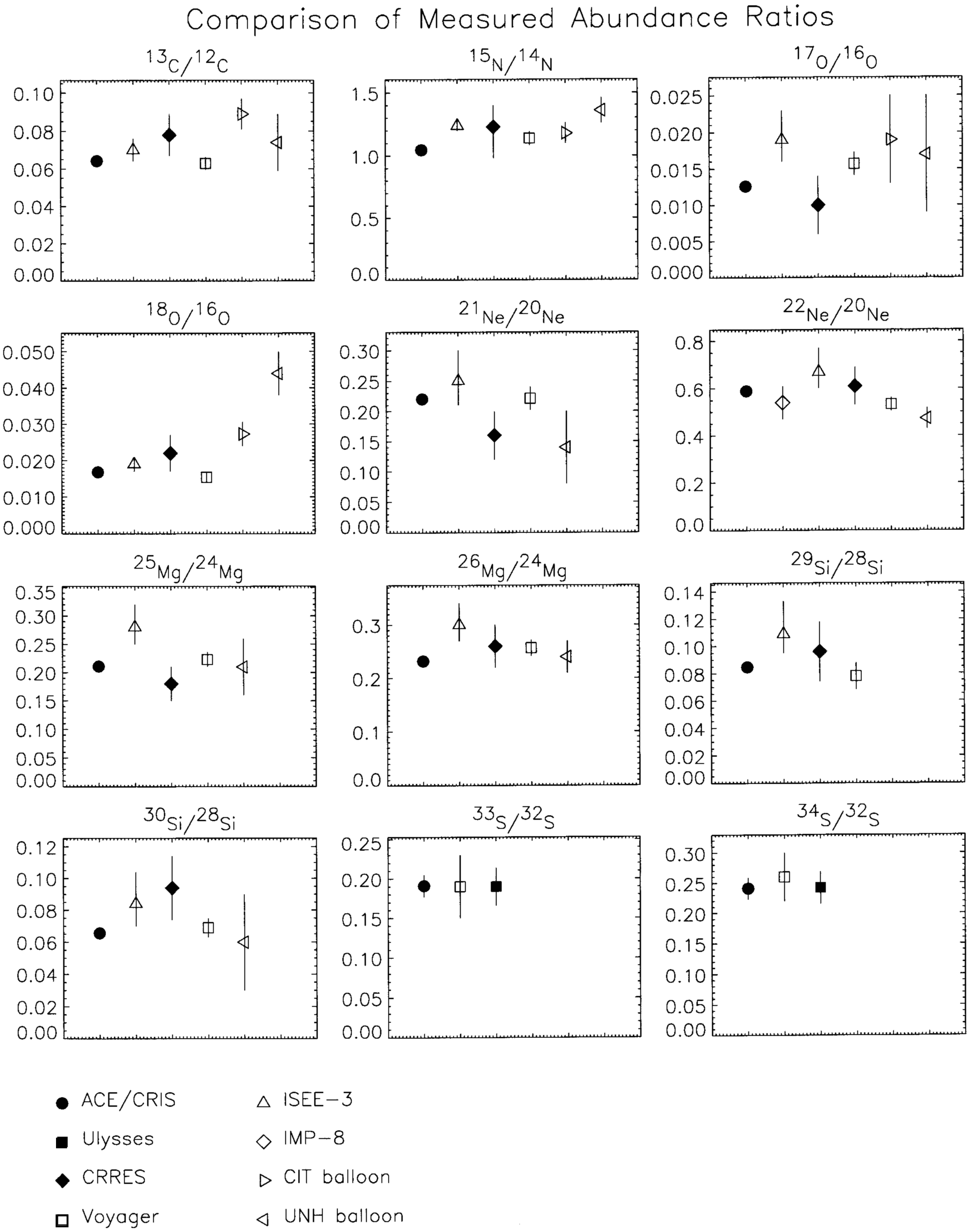

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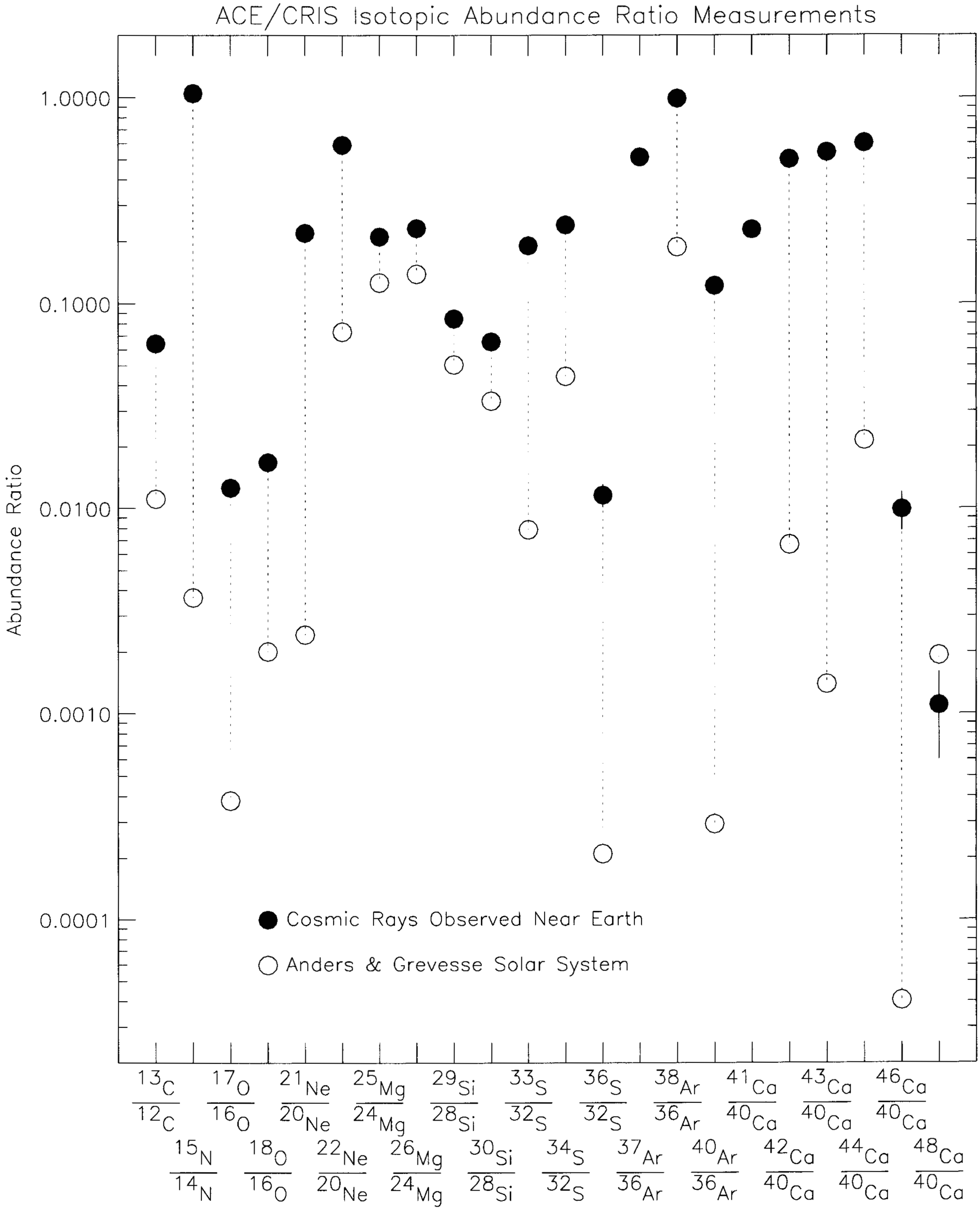

ACE/CRIS Isotopic Abundance Ratio Measurements
Abundance Ratio
1.0000
0.1000
0.0100
0.0010
0.0001
Cosmic Rays Observed Near Earth
Anders & Grevesse Solar System
13C/12C
15N/14N
17O/16O
18O/16O
21Ne/20Ne
22Ne/20Ne
25Mg/24Mg
26Mg/24Mg
29Si/28Si
30Si/28Si
33S/32S
34S/32S
36S/32S
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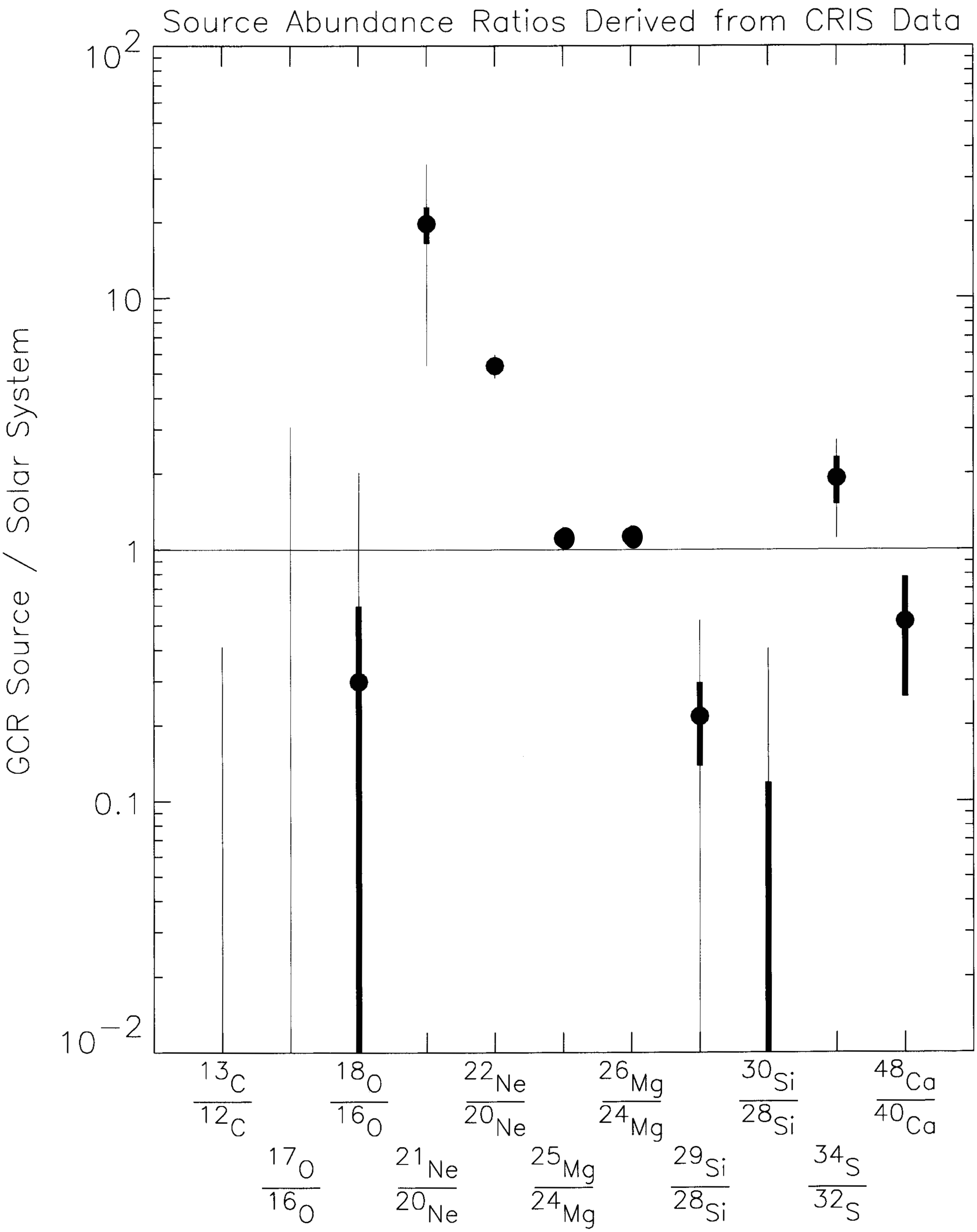
48Ca/40Ca



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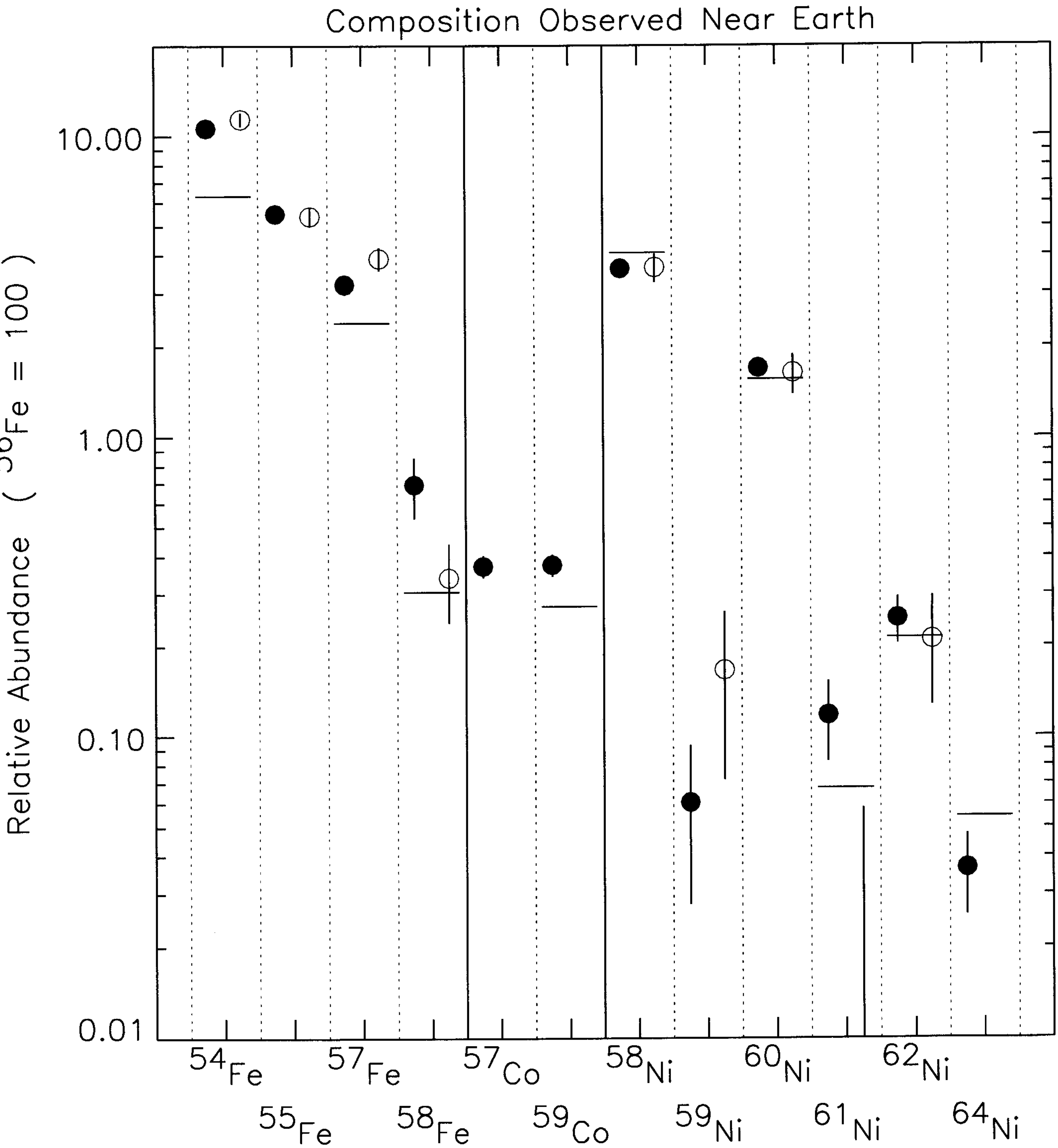

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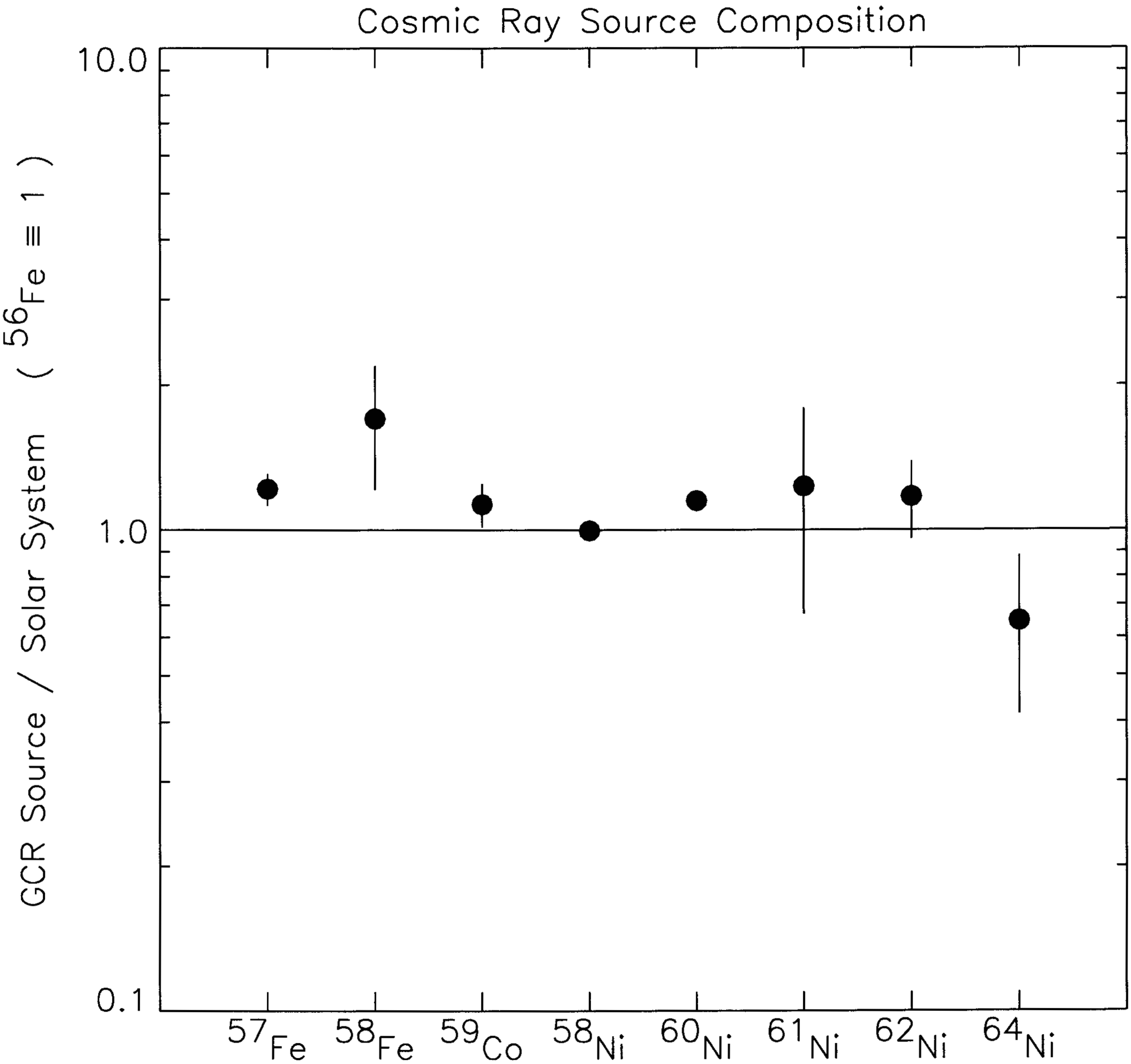

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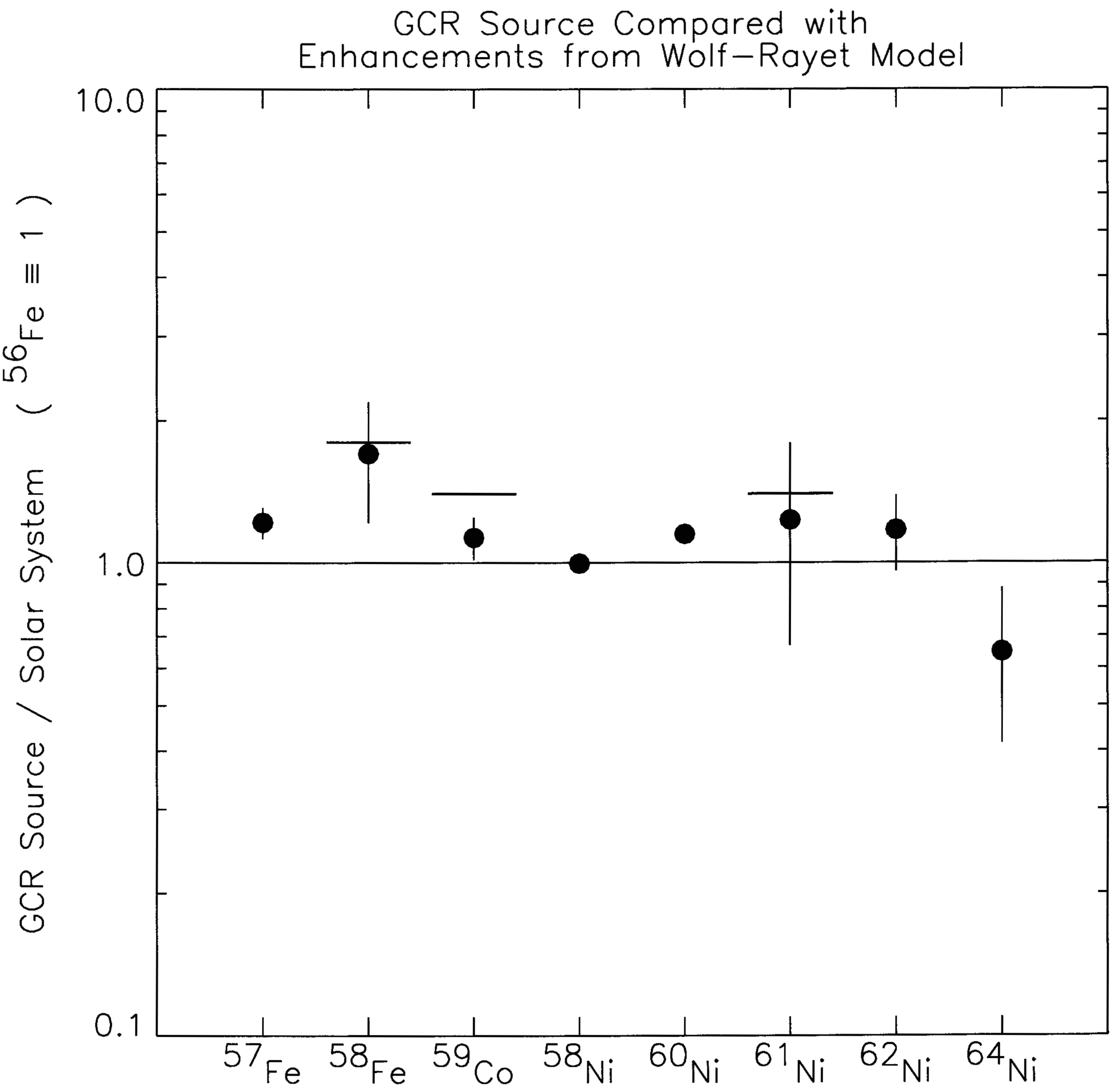

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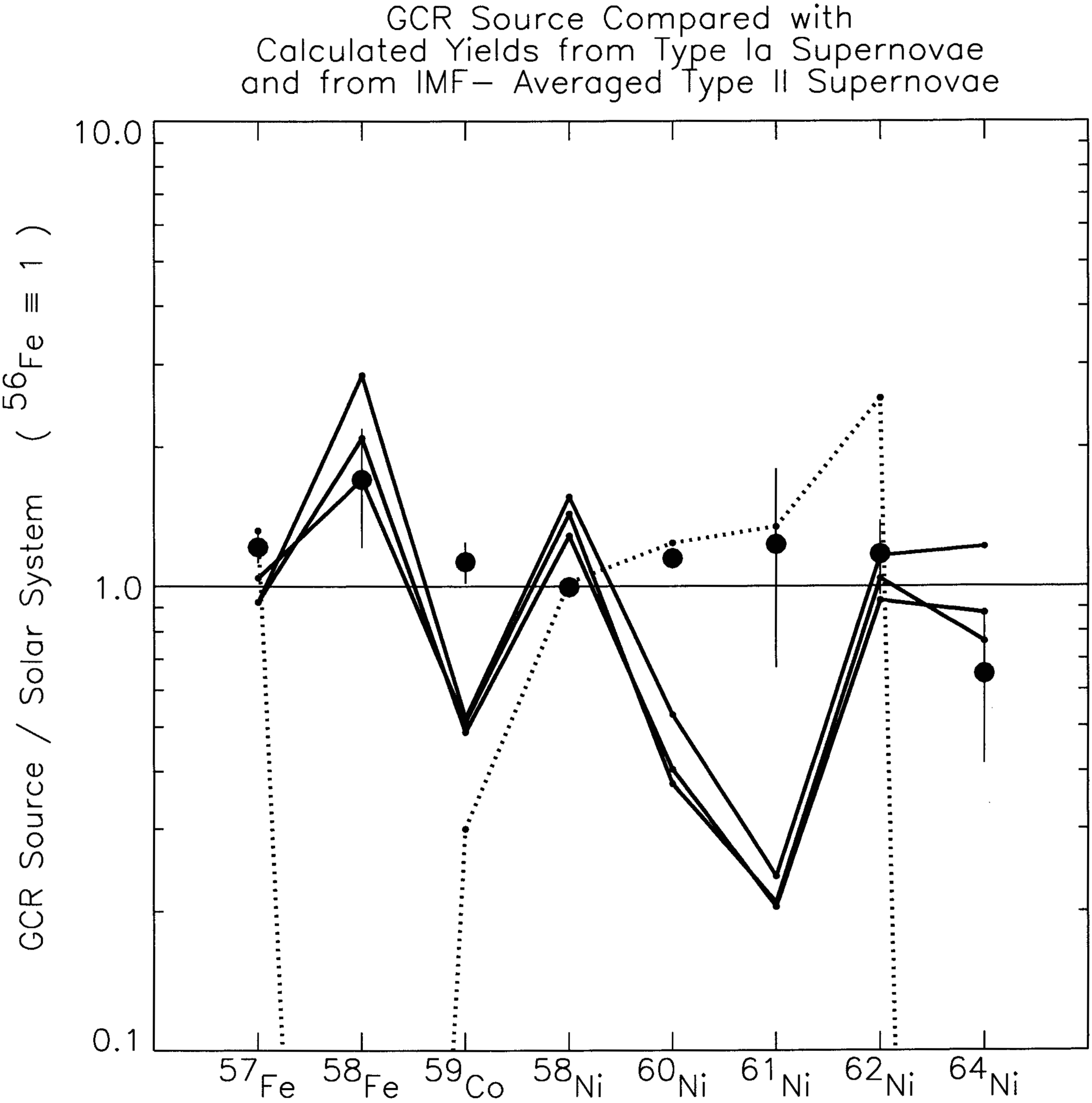

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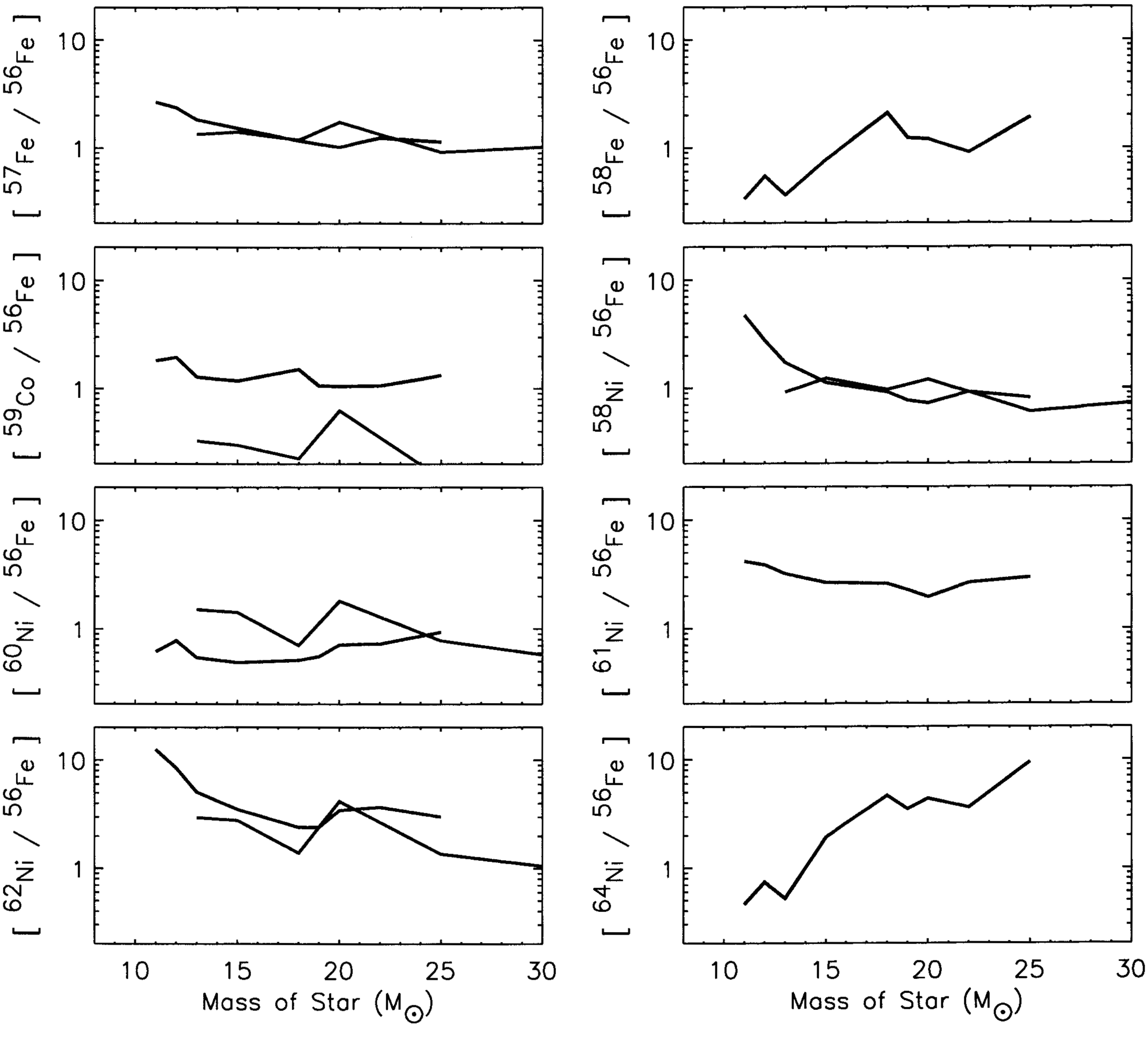
GCR Source Compared with Calculated Yields from Type II Supernovae of Various Masses



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CONCLUSIONS

- Cosmic-ray isotopic abundances are now measured for <u>all</u> stable isotopes for elements from H through Ni.

- Source isotopic composition can be derived for isotopes which are not dominated by secondaries produced during propagation. These include the major isotopes of Ne, Mg, Si, Fe, and Ni, and with larger uncertainties those of C and S.

- The isotopic composition of cosmic-ray source material is strikingly similar to the composition found in the solar system. Except for the well-established excess of ^{22}Ne, source isotope ratios differ from solar-system values by at most 10's of percent.

- The rare, neutron-rich isotope ^{48}Ca is now measured for the first time and the ratio to ^{40}Ca appears consistent with the solar system value (factor of 2 or better).

- The solar-like mix of isotopes of Fe and Ni suggests that types II and Ia supernovae contribute to cosmic-ray source material in proportions similar to their contributions to the solar system.